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MEMORANDUM

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A TURBOJET ENGINE OPERATED AT 1650° F

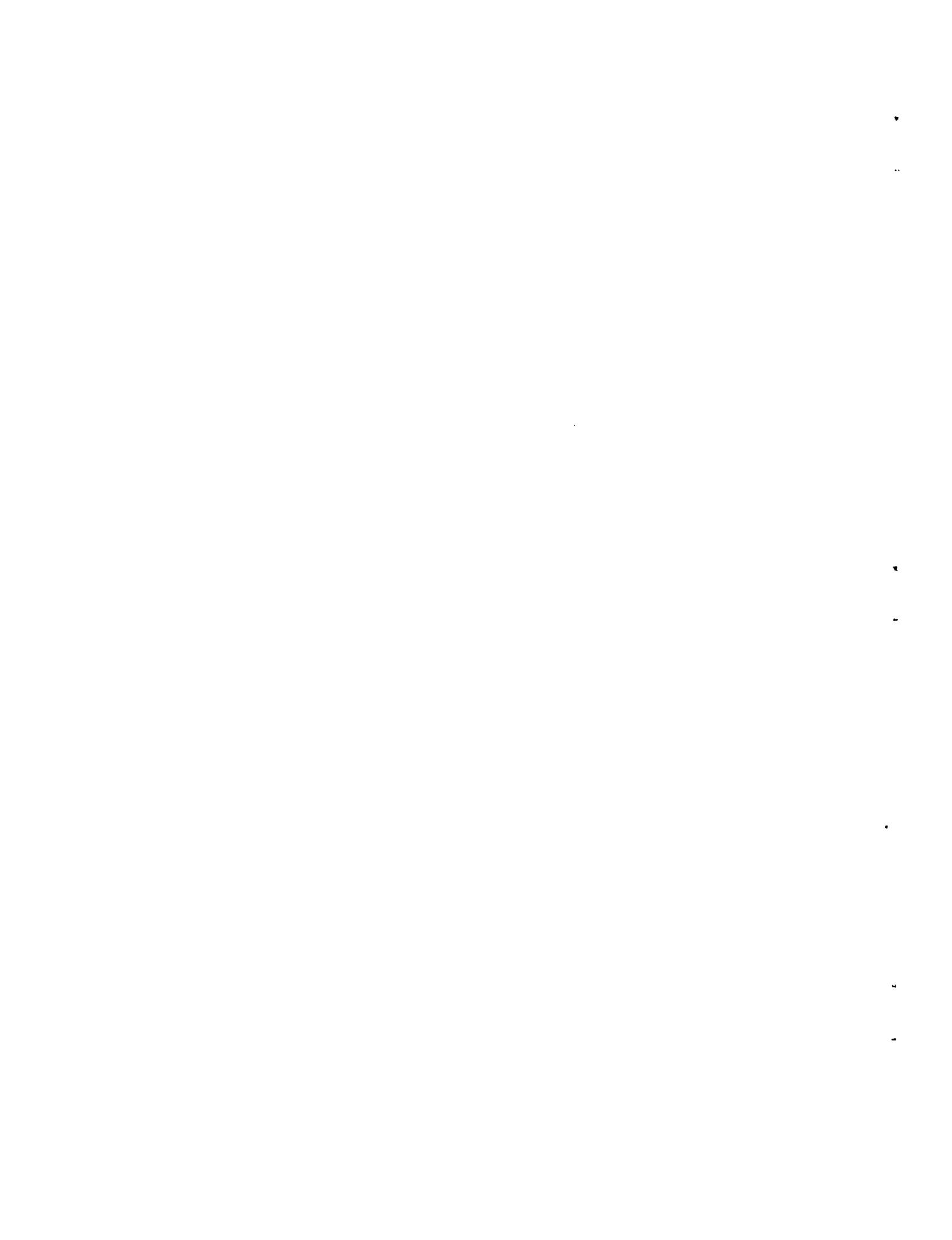
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Cleveland, Ohio

**NATIONAL AERONAUTICS AND
SPACE ADMINISTRATION**

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PERFORMANCE OF TWO BORON-MODIFIED S-816 ALLOYS

IN A TURBOJET ENGINE OPERATED AT 1650° F

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SUMMARY

S-816+B and modified S-816+B cast cobalt-base alloys were evaluated as turbine-bucket materials at 1650° F. Stress-rupture and tensile data obtained from these alloys had indicated satisfactory strength for engine operation at 1650° F. Although both alloys exhibited a limited ductility in room-temperature laboratory impact tests, there was a significant increase in impact resistance in the 1650° F tests.

Bucket failures began after 10 hours of engine testing and continued at various intervals during the $107\frac{1}{2}$ -hour test. Bucket lives were short relative to the predicted lives based on stress-rupture considerations (280 hr for S-816+B and 1750 hr for modified S-816+B). No significant difference was apparent in the performance of the two alloy groups.

The primary cause of bucket failures in both alloys was mechanical fatigue. Impact damage occurred as a direct result of bucket tip fatigue failures and was a secondary cause of bucket failures. The impact of small pieces of fractured bucket tips on surrounding buckets caused a relatively large amount of impact damage to buckets of both alloys. The amount of impact damage from induced fractures at the bucket midspan, which provided relatively large failed fragments, was no greater than that which occurred as a result of tip failures.

INTRODUCTION

Thrust of turbojet engines can be increased by raising the turbine-inlet gas temperature. This temperature is limited by the strength of materials at elevated temperatures, and much research has been done to develop new materials capable of withstanding higher temperatures. Within the last few years several high-strength alloys have been developed that

would permit turbojet engine operation at significantly higher turbine-inlet gas temperatures. Many of these have been nickel-base alloys (e.g., cast GMR 235, Udiment 500, wrought Inconel 70C, cast Guy alloy), in which the principal strengtheners in most instances were Ni₃Al, Ni₃Ti, or other intermetallic compounds.

Several of these alloys have been operated in controlled turbojet-engine tests at the Lewis Research Center (ref. 1). The general conclusions reached from those engine tests were that nickel-base alloys, both cast and wrought, have definite usefulness as bucket materials and are capable of operating satisfactorily at temperatures between 1600° and 1700° F, and that the impact resistance of such alloys is adequate for turbine-bucket applications even though the alloys may exhibit low elongation and low impact resistance in laboratory tests. By comparison with the nickel-base alloys, relatively little development has been done on cobalt-base alloys for turbojet buckets. Currently the two principal cobalt-base alloys used in turbine buckets are wrought S-816 and cast X-40, both of which have been used approximately 10 years. The physical properties of S-816 and X-40 do not permit operation at temperatures much in excess of 1500° F.

Extensive research has been done to improve properties of S-816. Several element additions were investigated, and results obtained with boron alloys (ref. 2) indicate that these alloys have stress-rupture lives superior to that of regular S-816 at high temperatures. Various amounts of boron were considered, and maximum stress-rupture properties were obtained with a 1-percent boron addition (S-816+B alloy). This addition raises the temperature for rupture in 100 hours at 25,000 psi from 1500° F to about 1650° F. The increase in stress-rupture strength was accompanied by a decrease in ductility, as may have been expected from the high combined boron and carbon content. The addition of 1 percent boron to S-816 reduced elongation and reduction-of-area in stress-rupture at 1600° F by approximately one-half; elongation dropped from 23 to 12 percent and reduction-of-area from 46 to 22 percent (ref. 2). Impact data were not reported.

Although ductility is an important criterion in the selection of turbine-bucket materials, the low ductility of an alloy may not preclude its use in this capacity. For example, Guy alloy has low impact resistance and less than half the measured tensile elongation of S-816, and yet Guy alloy buckets were operated in a turbojet engine without failure for 102 hours at 1650° F (ref. 1). Of particular significance was the fact that the buckets were not severely damaged when the compressor failed (at 102 hr) and many fragments from the forward part of the engine passed through the turbine wheel and struck the buckets. Alloy S-816+B might behave similarly and was therefore considered as a potential bucket material.

Subsequent to the development of S-816+B a modification of S-816+B alloy was made by increasing the chromium and cobalt content and decreasing the nickel content. This alloy (termed modified S-816+B throughout this report) has improved stress-rupture strength over the S-816+B alloy. Therefore this alloy was also considered for turbojet-engine buckets.

The present investigation was conducted to determine the performance of S-816+B and modified S-816+B in a turbojet engine; particular emphasis was given to a study of the resistance of the alloys to impact in the engine. Twenty-six buckets of each alloy were installed and operated in a J33-9 turbojet engine. This engine was operated for repeated cycles of 15 minutes at rated speed and 5 minutes at idle speed. At rated speed the midspan portion of the buckets was at a temperature of 1650° F and a nominal centrifugal stress of 18,900 psi. This combination of stress and temperature occurred at the so-called critical region of the bucket where stress-rupture failures are expected to occur. In addition to the engine tests, tensile and impact tests were made at both room temperature and 1650° F, and stress-to-rupture tests were run at 1650° F under stresses ranging from 18,000 to 40,000 psi.

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MATERIALS, APPARATUS, AND PROCEDURE

Turbine Buckets

Turbine buckets of S-816+B and modified S-816+B were obtained from a commercial source in the as-cast condition. Both alloys were cast in air and poured at a metal temperature between 2675° and 2700° F into molds preheated to 1600° F. Six buckets were cast from each heat. The nominal chemical compositions of the S-816+B, modified S-816+B, and regular S-816 are given as percentages in the following table:

Alloy	Co	Ni	Cr	W	Mo	Nb-Ta	C	B	Si	Mn	Fe
S-816	44	20	20	4	4	4	0.4	-	0.6	1.20	5(Max.)
S-816+B	Bal. (43)	20	20	4	4	4	0.4	1	0.4	1.0	3(Max.)
Modified S-816+B	Bal. (53)	5	25	4	4	4	0.4	1	0.4	1.0	2(Max.)

Two buckets of each alloy were selected at random and checked for dimensional accuracy by taking cross-sectional area measurements of the airfoils. The buckets were within dimensional tolerances, although slightly under nominal dimensions in certain areas. All buckets were inspected using radiography and postemulsified zyglo. Buckets selected for engine operation were free of defects detectable by radiographic inspection and free of surface defects, detectable by zyglo, along the

leading and trailing edges and in the fillet area. A limited number of small surface defects were permitted in the central portion of the airfoil and in the base.

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Engine Operation

Fifty-four test buckets were installed in a J33-9 turbojet engine. Of the 54 buckets, 26 were S-816+B and 26 were modified S-816+B. The other two buckets were thermocoupled standard S-816 buckets used for setting engine operating conditions and were not part of the bucket evaluation tests. The engine was operated for repeated cycles of 15 minutes at rated speed (11,539 rpm) and 5 minutes at idle speed (4000 rpm). Only time at rated speed is considered in the discussion of bucket life. The engine was stopped only when buckets failed or for engine repair. Following a failure all buckets were removed and examined for possible damage.

During the engine evaluation of S-816+B and modified S-816+B, bucket stresses and temperature were controlled by regulating the engine speed and exhaust-nozzle opening, respectively. For rated-speed operation these values were maintained the same as those shown in the temperature-distribution curve of figure 1. Since S-816 does not have adequate strength to operate at 1650° F for long times under rated-engine-speed stresses, a 1-inch section was cut from the tip of the thermocoupled airfoils to reduce centrifugal stresses to an acceptable level.

Stress and Temperature Distribution

The distributions of centrifugal stress and temperature in bucket airfoils during engine operation at rated speed are shown in figure 1. The centrifugal stresses were calculated by the method described in reference 3 and represent average stresses over the entire airfoil cross section. To obtain the bucket airfoil temperature distribution prior to evaluating the S-816+B and modified S-816+B buckets, a full turbine wheel of standard S-816 buckets was operated in the engine for a few minutes. The temperatures were obtained from thermocouples installed in the buckets at midchord and connected to a recording device through slirings, using the methods described in reference 4.

Figure 1 also shows the predicted-engine-life curve for buckets of each alloy if failure results solely from a combination of centrifugal stress and temperature. These curves were constructed using analytical and graphical extrapolation of stress-rupture data to determine the potential stress-rupture life at various spanwise stations along the airfoil. The most important portions of these curves are those which indicate the location of minimum bucket life. These portions of the curves were

obtained directly from stress-rupture data and not from extrapolations. The remaining portions of the curves should be considered qualitative. Since the greater part of the curve is based on extrapolated data, a critical zone of minimum life is selected rather than the minimum point. This zone indicates the region in which the buckets should fail by stress-rupture and the stress-rupture lives to be expected. In addition to centrifugal stresses, other factors such as vibratory stresses, thermal shock, and corrosion may accelerate bucket failure.

Bucket Elongation Measurements

Three buckets of each alloy were scribed as shown in figure 2. The elongation of the various sections of the scribed airfoils was measured with an optical extensometer after completion of 10, 55, and 106 hours of engine operation. Elongation readings were taken to the nearest 0.0001 inch in each 1/2-inch gage length. However, because of the width of the scribed marks, bowing of bucket airfoils, and human error, elongation readings were sensitive to ± 0.001 inch or ± 0.2 percent of the gage length.

Macroexamination of Failed Buckets

Following a turbine-bucket fracture the engine was stopped and all buckets were removed and examined macroscopically. Postemulsified zyglo was used to detect slight cracks and flaws not readily visible to the naked eye. Buckets were considered as failed and removed from the test if they had fractured or were in imminent danger of fracture. Unfractured buckets were removed if cracks or serious impact damage was evident. If impact damage was confined to the upper 1/2 inch of the airfoil, the bucket was not removed.

Metallographic Examination and Hardness Tests

Metallographic studies and hardness tests were made on two buckets of each alloy in both the as-cast and engine-operated conditions. Similar data were taken from all failed stress-rupture bars (bars discussed in next section).

Metallographic studies and hardness tests were made on chordwise sections from the midspan portions of the as-cast bucket airfoils. Failed buckets and stress-rupture bars were examined in a similar manner in areas immediately adjacent to fractures.

Stress-Rupture and Tensile Tests

Stress-rupture and tensile tests were run on specimens obtained from randomly selected turbine buckets of each alloy in the as-cast condition. Figure 3 shows the test bar and that portion of the airfoil from which the test bars were obtained. Two test bars were obtained from each bucket. Stress-rupture lives for S-816+B and modified S-816+B were established at 1650° F for a range of stress from 18,000 to 40,000 psi. Two tensile tests were performed at 1650° F for each alloy.

Impact Studies

Laboratory impact studies. - Laboratory impact tests were performed for both alloys and for Guy alloy (as a standard for comparison) in the as-cast condition, using a low-capacity Izod impact tester. The tester is shown in figure 4 and is described in reference 5. Tests were performed at room temperature and at 1650° F with 3/16- by 3/16- by 1 $\frac{1}{2}$ -inch unnotched impact bars machined from the base section of buckets. The test bars were inserted in the gripping device to a depth of 1/2 inch, and the point of impact of the pendulum was 1/8 inch from the free end of the bar. The total capacity of the pendulum was 25.5 inch-pounds, and the striking velocity was 135 inches per second.

Figure 5 shows the heating and gripping arrangement used in the impact tests at 1650° F. A battery of three propane torches was manually directed at the free length of the test bar. Two thermocouples were attached on opposite sides of the test bars, as shown in figure 5. The thermocouples were located where the specimen was expected to break, at a point just above the gripping device. When the temperature reached 1650° F, the torches were removed and the pendulum was released. To minimize heating of the steel vise jaws, sections of Transite were inserted between the specimen and the jaw faces. While the Transite was not needed in room-temperature tests, the same procedure was used to avoid possible variables in gripping.

The impact-test apparatus was being used under conditions for which it was not designed in the 1650° F tests; also, the specimens, because of their physical dimensions, were of necessity machined from the base section of the buckets. The base region is not necessarily representative of the properties of the airfoil. As a result, the data may be open to question and not necessarily representative of the best properties of the materials. Despite these drawbacks qualitative data were obtained with which to compare the relative impact strengths of the two alloys and Guy alloy. This comparison was of interest because Guy alloy has similar ductility to the alloys under investigation and has performed satisfactorily in engine operation, as described previously.

Engine impact studies. - Additional engine tests were performed to determine the amount of impact damage that would result if a bucket failed at midspan. This was necessary, since all bucket fractures occurred in the upper portion of the airfoil, as is shown later. As a result of these fractures near the tip, relatively small portions of the failed airfoils struck surrounding buckets. Stress-rupture failures that normally occur at midspan often cause relatively large pieces of bucket material to be impacted upon surrounding buckets. This type of failure was induced artificially simply by sawing buckets partially through at the midspan of the airfoil, 2 inches above the base. Upon completion of the endurance portion of the engine test, one bucket was removed from the turbine wheel and replaced by an artificially weakened bucket. The engine was then accelerated to rated speed (max. centrifugal bucket stress) until the weakened bucket failed. Three engine runs of this type were attempted.

RESULTS

Engine Performance of S-816+B and Modified S-816+B Buckets

Figure 6 shows the failure times and mechanisms for turbine buckets of both alloys. Failures of both S-816+B and modified S-816+B buckets began after only 10 hours of engine operation and continued at various intervals throughout the test. The test was discontinued after $107\frac{1}{2}$ hours of operation, at which time 74 percent of the S-816+B buckets and 58 percent of the modified S-816+B buckets had failed.

Failures occurred by two mechanisms during the test. These were tip fatigue and impact damage induced in other buckets by the tip failures. The engine performance of S-816+B and modified S-816+B buckets was similar, although the modified S-816+B buckets appeared to be slightly superior on the basis of median life. In the computation of median lives, only bucket tip failures were included. Modified S-816+B had a median life of $107\frac{1}{2}$ hours, while S-816+B had a median life of $91\frac{1}{2}$ hours.

Bucket Tip Failures

Tip failures were initiated at the trailing edges, approximately 1 inch from the tip of the airfoil. Cracks progressed inward until stress on the reduced cross-sectional area of the airfoil caused fracture (fig. 7). In some cases cracked buckets were discovered during inspection. Such buckets were considered as failed and removed. Bucket tip failures were observed in all failed buckets, except those removed because of impact damage.

Microexamination revealed that the trailing-edge cracks were trans-crystalline, which is typical of those caused by mechanical fatigue. Figure 8 is a photomicrograph of a crack in a typical failed bucket.

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Impact-Damage Failures

Impact damage accounted for numerous bucket failures of both alloys. The brittleness of both alloys is evident in figure 9, which shows typical impact damage. Twenty-one buckets were removed from the turbine wheel during the engine test because of this type of damage.

Elongation Measurements

Of the six buckets scribed for elongation measurements, only one of each alloy remained in operation for the entire test. The others had previously been removed because of failure. Figure 10 shows the elongation of the two central zones of the two bucket airfoils during 106 hours of operation. The S-816+B airfoil showed a maximum elongation of 1.1 percent in zone 3. This is greater than the elongation of the modified S-816+B bucket, which elongated approximately 0.7 percent in the same zone.

Microstructure and Grain Size

Photomicrographs of typical as-cast structures of the two alloys are shown in figure 11. Except for the more massive carbide and boride network and the slight amount of precipitation in the matrix of the S-816+B alloy, the as-cast microstructures of both alloys appeared quite similar.

Photomicrographs of engine-operated buckets of both alloys are shown in figure 12. Precipitation in the matrix increased with increased engine operating times at 1650° F. Modified S-816+B appears to be the more stable of the two alloys in that precipitates apparently formed at a slower rate.

Macroetching of selected turbine buckets revealed that the grain size of both alloys was fairly uniform from bucket to bucket. In all cases the grain size was smaller at the edges and larger in the central portion of the airfoil. Macroetched buckets did not photograph well and thus are not presented in this report.

Hardness Tests

The results of hardness tests obtained from stress-rupture bars and buckets of both alloys before and after engine operation are shown in

table I. Aging had little effect on the hardness of S-816+B, and its hardness remained essentially constant throughout the range of test conditions investigated. All hardness readings on S-816+B, including those from rupture bars, were in the range Rockwell C-36.5 to 39.5 and averaged 37.5.

Modified S-816+B was harder than S-816+B in the as-cast condition and increased in hardness after initial engine operation. The average hardness increased from Rockwell C-41.3 to about 45.0 with 10 hours of engine operation and did not increase more with longer operating times. Hardness of failed modified S-816+B rupture bars from the as-cast condition increased to about the same hardness as the engine-operated buckets, with values ranging from Rockwell C-44.5 to 47.0.

Stress-Rupture and Tensile Tests

The stress-rupture results obtained for both alloys at 1650° F are shown in figure 13 and table I. As a basis for comparison, the stress-rupture data for standard S-816 at 1650° F are also shown. The latter curve was interpolated from unpublished 1600° and 1700° F data. From this figure it is evident that both S-816+B and modified S-816+B are greatly superior to standard S-816 in stress-rupture strength. The 100-hour rupture strengths at 1650° F for S-816, S-816+B, and modified S-816+B are respectively 12,000, 23,500, and 29,500 psi. The percentage elongation is also shown in figure 13. A considerable amount of intergranular cracking was observed in the test sections of the stress-rupture bars, and this contributed to the high elongation measurements.

Table II lists results of 1650° F tensile tests on specimens obtained from as-cast buckets and unpublished room-temperature data. Modified S-816+B was stronger than S-816+B at both room temperature and 1650° F. Both alloys showed considerable tensile ductility at 1650° F. The elongation obtained for modified S-816+B alloy, 10.5 percent, was greater than that for S-816+B alloy, which was 6.5 percent. Some of this elongation may be attributed to intergranular tears, which were visible in the surface of the test bars, and perhaps the elongation values are not indicative of the actual ductility of the materials. However, necking of the test bars was quite evident in both alloys and particularly in the S-816+B test bars. This is shown by the reduction-of-area values obtained.

Impact Studies

The results of the laboratory impact tests are shown in table III. Scatter occurred in both room-temperature and 1650° F test results. However, as mentioned previously, while numerical values may not be

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strictly accurate, comparisons of relative impact resistance may be made. The average room-temperature impact strengths of S-816+B and modified S-816+B were about equal and were about half that obtained for Guy alloy under the same test conditions. The impact strength of all three alloys was higher at 1650° F than at room temperature; however, the superiority of the Guy alloy was much less pronounced at 1650° F. The impact strength of the two alloys under investigation approximately doubled, while that of Guy alloy increased from an average of 11.5 to an average of 15.2 inch-pounds in going from room temperature to 1650° F.

In the engine impact studies, fragments from the upper half of the artificially weakened buckets were expected to damage the remaining buckets more severely than fragments from the "normal" tip failures. Two of the weakened buckets failed during engine acceleration at 6000 and 8000 rpm, and the third bucket failed at rated speed (11,539 rpm). Following each of the three failures all turbine buckets were inspected for damage. The amount of impact damage that resulted from these intentional failures was about the same as that which occurred during the normal engine test as a result of bucket tip failures (fig. 9). To this extent at least, the impact damage of the alloys was insensitive to the size of the failed fragment.

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DISCUSSION

Most of the buckets in this investigation failed very early relative to their potential lives based on stress-rupture considerations alone. The principle cause of bucket failures was mechanical fatigue, which occurred in the airfoil tip. This mechanism not only reduced the life of the majority of buckets of each alloy, relative to its predicted stress-rupture life (280 hr for S-816+B and 1750 hr for modified S-816+B buckets (fig. 1)), but it almost equalized the performance of the two alloy groups. From a practical standpoint, there was no difference in performance of the two groups of buckets, since bucket failures of both alloys began after 10 hours of operation and continued to occur at more or less similar intervals throughout the test. At the time the test was discontinued ($107\frac{1}{2}$ hr) 74 percent of the S-816+B and 58 percent of the modified S-816+B buckets had failed.

Failure of buckets at the tip, where centrifugal stress is very low are the result, almost solely, of vibratory stresses and as such are classified as "pure" mechanical fatigue failures. Since this mode of failure has been encountered only rarely with other materials studied in the J33-9 engine operated under similar conditions, S-816+B and modified S-816+B appear sensitive to mechanical fatigue. It should be noted, however, that slight modifications of the engine design, the engine operating conditions, and the bucket design can greatly alter the resonant vibratory conditions and thus, perhaps, improve the fatigue life of turbine buckets.

Impact damage was a secondary cause of bucket failures and was a direct result of bucket tip failures. The impact of small pieces of fractured bucket tips on surrounding buckets caused a relatively large amount of impact damage (fig. 9), as described previously.

The relatively large amount of impact damage is contrary to what might have been expected from the elongation data obtained from stress-rupture and tensile tests at 1650° F (fig. 13 and table II). These indicated considerable ductility. Also, the Izod impact tests at 1650° F (table III) indicated that the two alloys were only slightly weaker than Guy alloy in impact strength. While its impact strength was not particularly high, Guy alloy had displayed satisfactory impact resistance during engine operation (ref. 1), as noted previously. Possible inaccuracies in the laboratory test impact data due to the testing methods employed, as mentioned in the procedure section, could perhaps account for some deviation from expected behavior. A more reasonable explanation of the apparent anomaly might be made if more were known about the effect on impact resistance of the impact velocities in the engine and those encountered in the test apparatus. The impact resistance of the S-816+B alloys may have been more adversely affected by increased impact velocity than was the impact resistance of Guy alloy. Perhaps the room-temperature low-velocity laboratory impact tests of the alloys provide a better indication of their relative impact resistance under elevated-temperature high-velocity engine impact conditions than do elevated-temperature low-velocity laboratory tests. As noted earlier, the room-temperature impact strengths of the two S-816+B alloys were about half that of Guy alloy (table III). If the foregoing postulation were valid, the impact damage observed in the engine tests with the two S-816+B alloys as compared with Guy alloy would be reasonable.

If, during the course of the engine test, a bucket had failed in the midspan, where most failures have been observed in earlier engine studies, the fractured piece would have had more than twice the mass and kinetic energy of a fragment resulting from a tip failure. The impact damage resulting from such a failure would be expected to give a better indication of the impact resistance of the alloys and the potential seriousness of impact. Tests in which large impacting particles were provided by partially cutting certain buckets at the midspan prior to engine operation indicated that the amount of impact damage resulting from each of these intentional failures at the midspan was no greater than that which had occurred as a result of tip failures. The possibility exists that the failed fragments of the bucket hit the shroud band before hitting any of the buckets and were, in so doing, shattered into smaller pieces. If this was the case, the particles that impacted the buckets were not appreciably larger than those resulting from tip failures. In any event the impact damage that resulted from failures of buckets of these alloys at midspan was not greater than that which resulted from tip failures.

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SUMMARY OF RESULTS

The results obtained from an evaluation of S-816+B and modified S-816+B as possible turbine-bucket materials for use at 1650° F are as follows:

1. Bucket failures of S-816+B and modified S-816+B began after 10 hours of engine operation and continued at various intervals throughout the $107\frac{1}{2}$ -hour test. At the completion of the test 74 percent of S-816+B buckets and 58 percent of the modified S-816+B buckets had failed. No significant difference was apparent in the performance of the two alloy groups.

2. The primary cause of bucket failure in both alloys was mechanical fatigue. The failures were initiated by fatigue cracks which occurred on the trailing edge about 1 inch below the tip. This mechanism reduced the life of the majority of the buckets of each alloy relative to its life predicted from stress-rupture considerations. (The predicted lives were 280 hr for S-816+B and 1750 hr for modified S-816+B.)

3. Impact-damage failures occurred as a result of bucket tip failures. Small pieces of fractured bucket tips struck surrounding buckets and caused a relatively large amount of damage to buckets of both alloys.

4. The amount of impact damage to buckets resulting from induced fractures at the bucket midspan (relatively large failed fragments) was no greater than that which occurred as a result of tip failures, the usual failure mechanism in this investigation.

Lewis Research Center

National Aeronautics and Space Administration
Cleveland, Ohio, December 4, 1958

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TABLE I. - HARDNESS-TEST RESULTS

(a) Turbine buckets.

Engine operating time, hr	S-816+B hardness, Rockwell C- (a)	Modified S-816+B hardness, Rockwell C- (a)
0	37.3	41.3
10	37.5	45.3
103	----	44.5
107	38.4	----

(b) Stress-rupture bars tested at 1650° F.

S-816+B			
Stress, psi	Test life, hr	Hardness, Rockwell C- (a)	Elongation, percent
18,000	580.7	37.0	12
21,000	133.6	36.5	20
25,000	47.2	36.5	21
30,000	26.0	39.5	14
32,000	10.2	37.5	16
Modified S-816+B			
Stress, psi	Test life, hr	Hardness, Rockwell C- (a)	Elongation, percent
18,000	2170.0	44.5	14
20,000	1284.5	45.0	16
25,000	284.4	45.0	21
30,000	78.8	46.5	19
40,000	6.8	47.0	14

^aAverage of seven or more readings (same or different specimens).

TABLE II. - TENSILE PROPERTIES

Alloy	Temperature	0.2-Percent offset yield strength, psi	Ultimate strength, psi	Elongation, percent	Reduction of area, percent
S-816+B	^a Room	77,771	107,900	1.2	1.2
S-816+B	^b 1650° F	42,925	52,750	6.5	14.4
Modified S-816+B	^a Room	95,500	113,000	0.5	0.5
Modified S-816+B	^b 1650° F	57,500	64,500	10.5	11.9

^aUnpublished data.^bAverage of two tests.

TABLE III. - IZOD IMPACT-TEST RESULTS

Alloy	Measured impact resistance, in.-lb	
	Room temperature	1650° F
S-816+B	5.6	17.6
	5.2	11.2
	8.0	11.8
	7.6	13.9
	Av. 6.6	13.0
		Av. 13.5
Modified S-816+B	5.8	9.2
	5.1	12.0
	4.0	12.6
	6.6	13.0
	Av. 5.4	11.0
		Av. 11.6
Guy	15.2	13.1
	10.0	11.3
	11.8	18.6
	10.3	17.7
	10.7	Av. 15.2
	Av. 11.6	

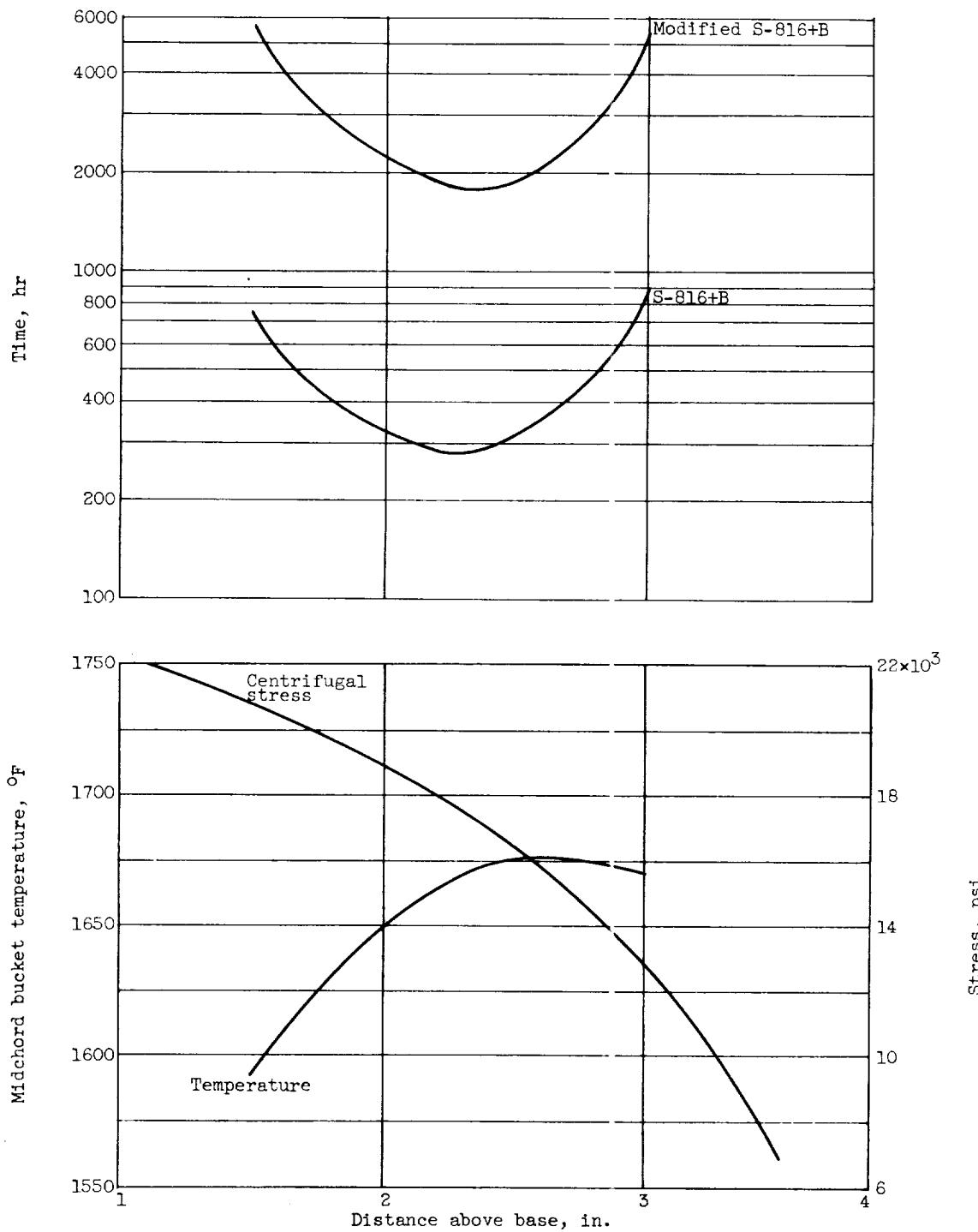


Figure 1. - Nominal temperature-stress distribution and minimum stress-rupture lives of bucket airfoils.

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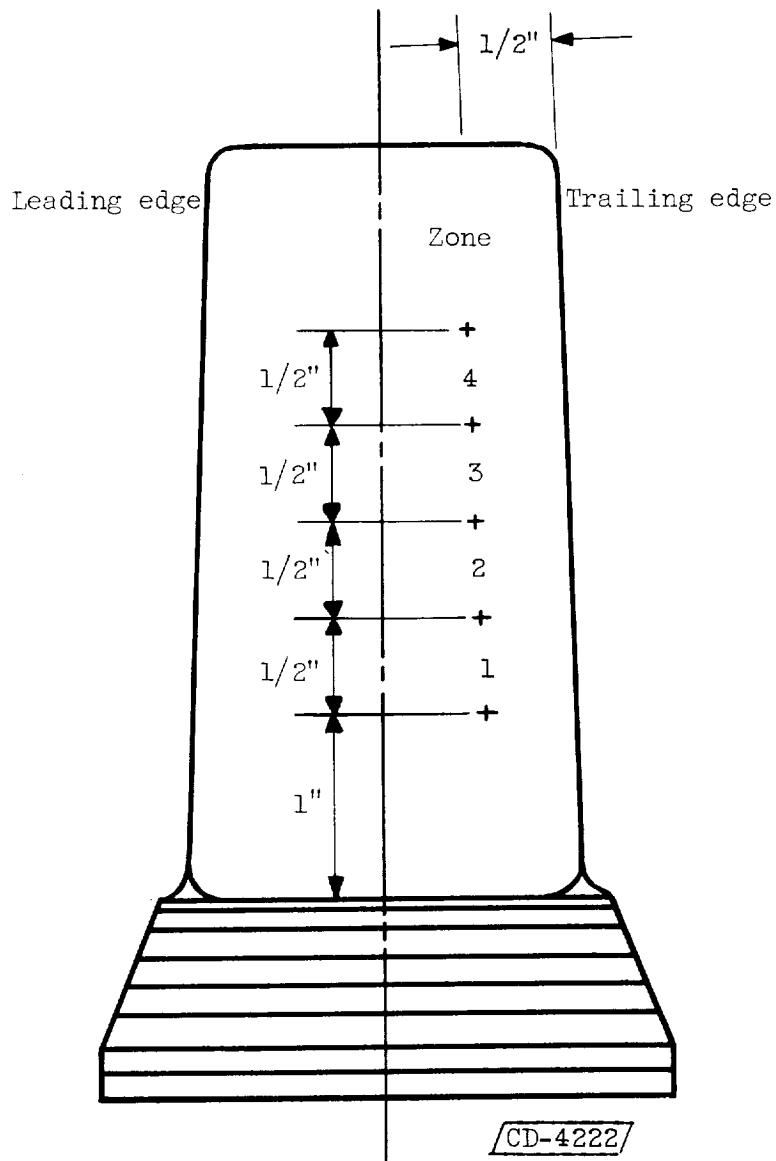


Figure 2. - Scribed bucket for elongation measurements.

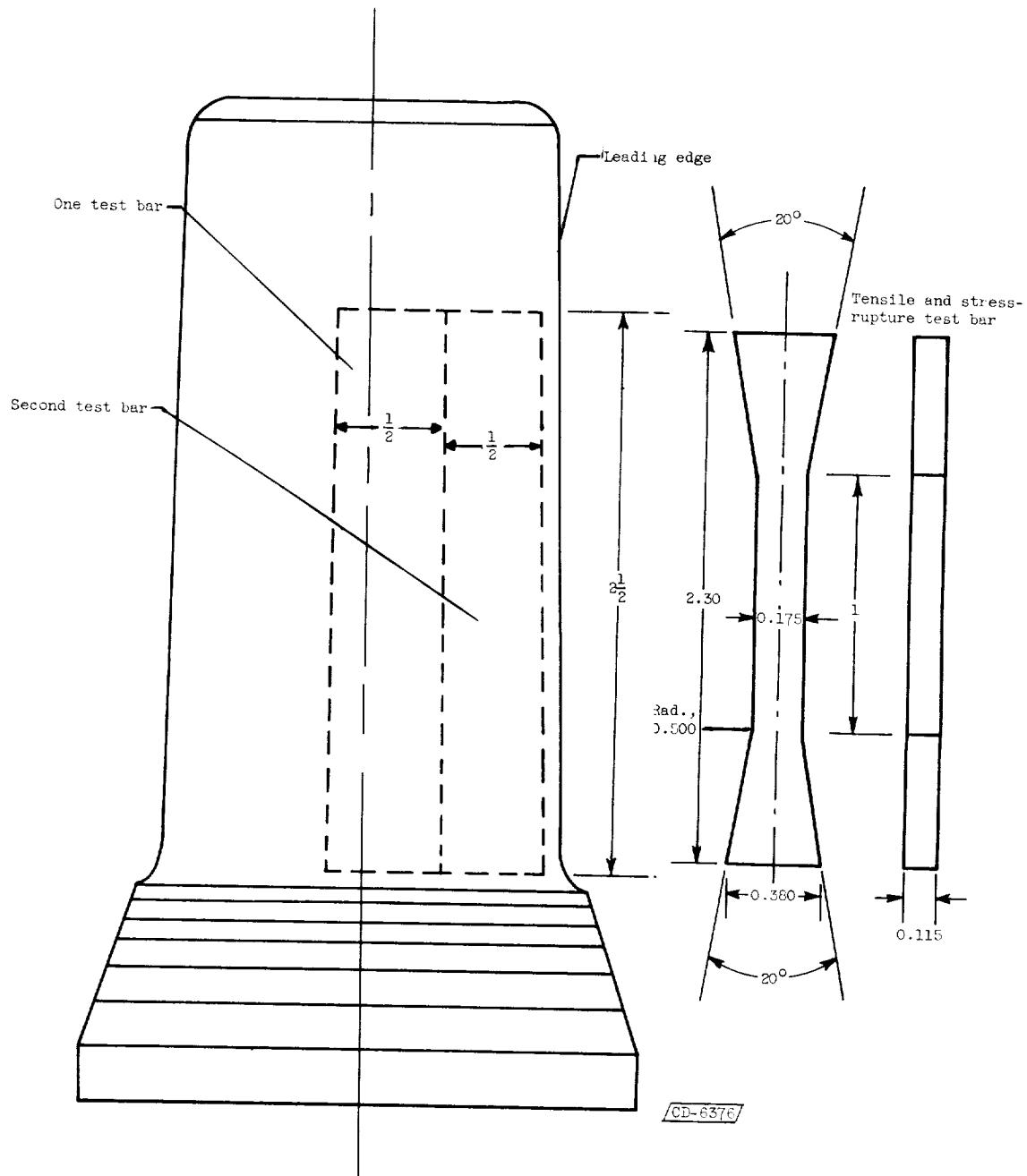


Figure 3. - Stress-rupture and tensile bars and zone from which they were obtained. (Dimensions in inches.)

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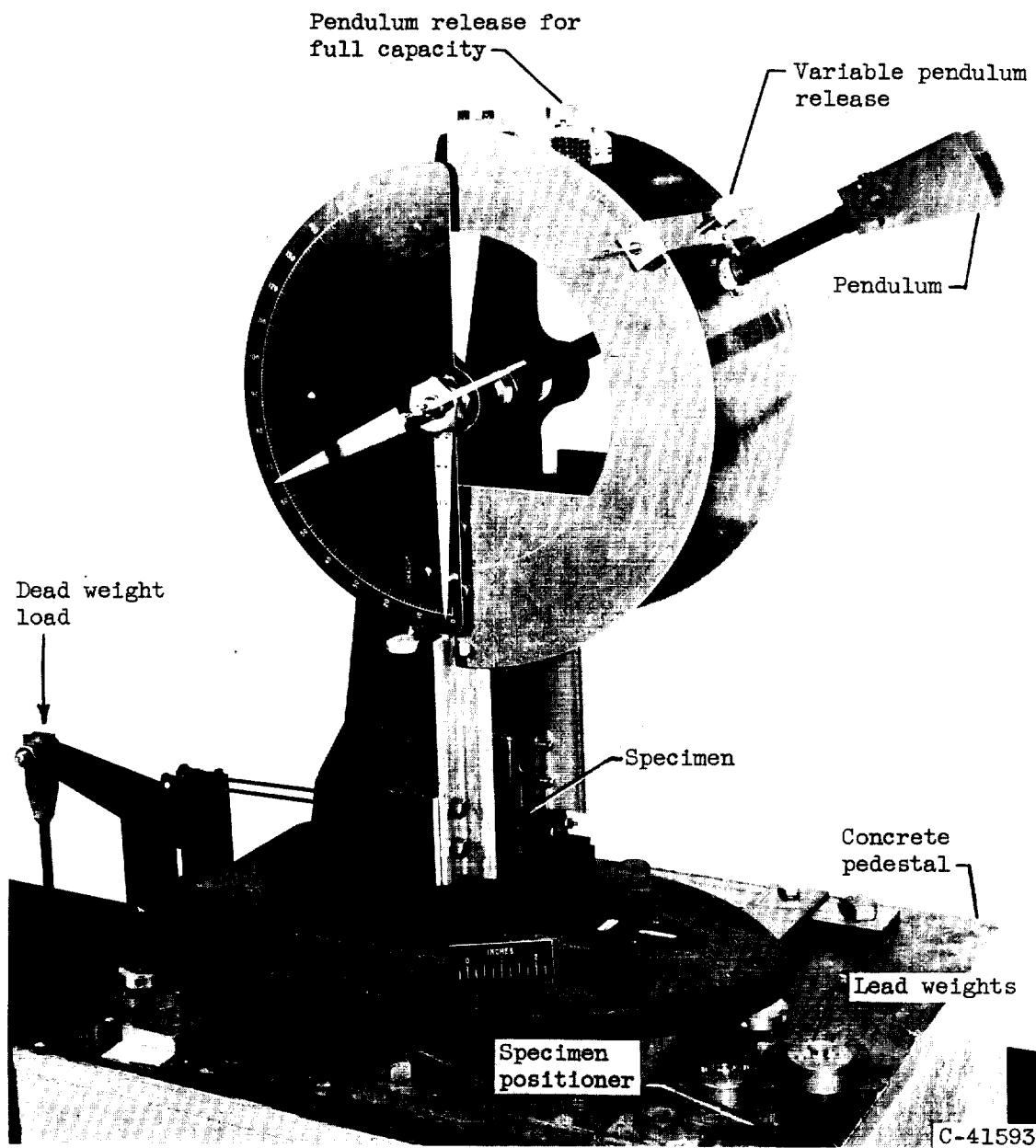


Figure 4. - Modified Izod impact-test apparatus.

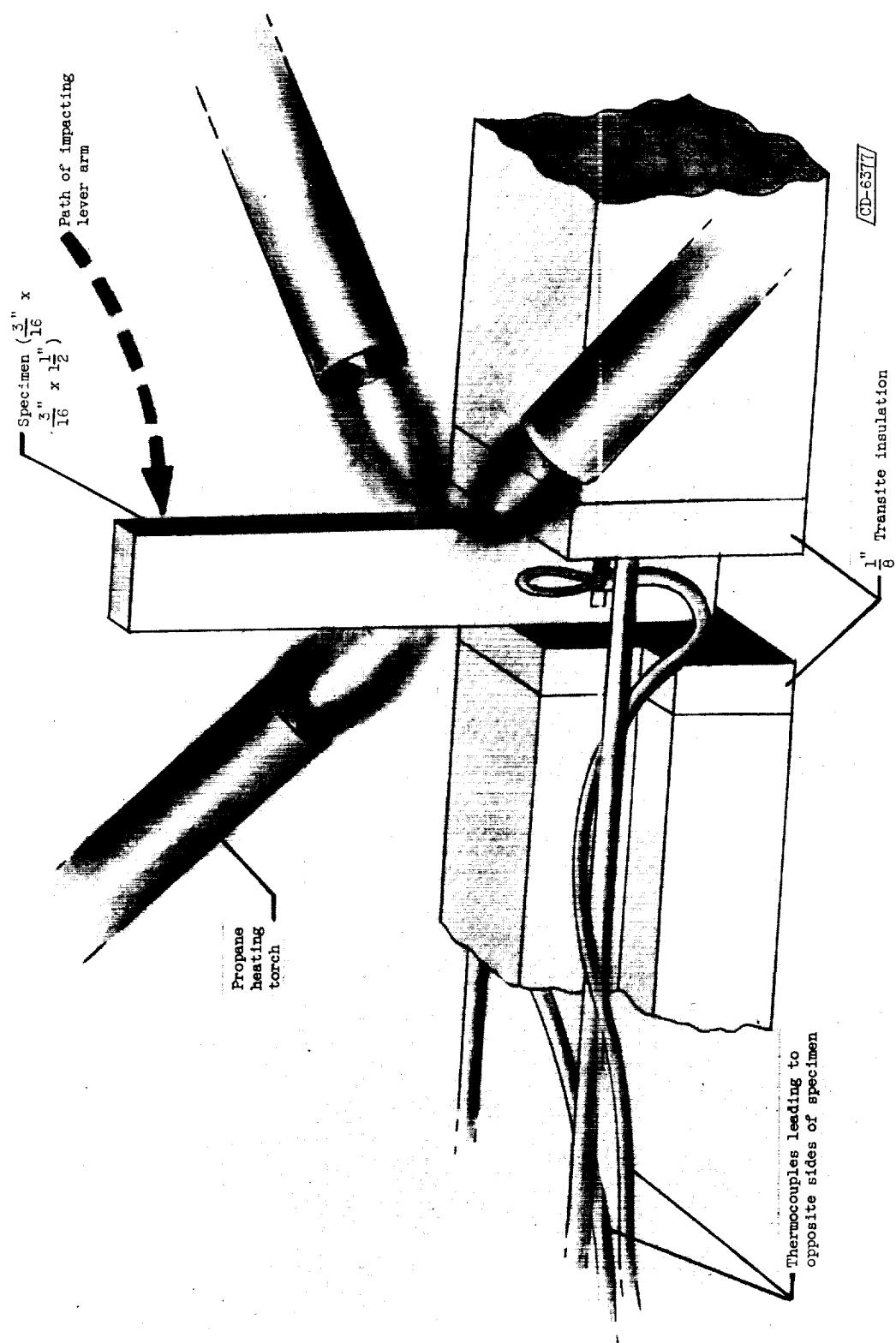


Figure 5. - Sketch of high-temperature impact test apparatus.

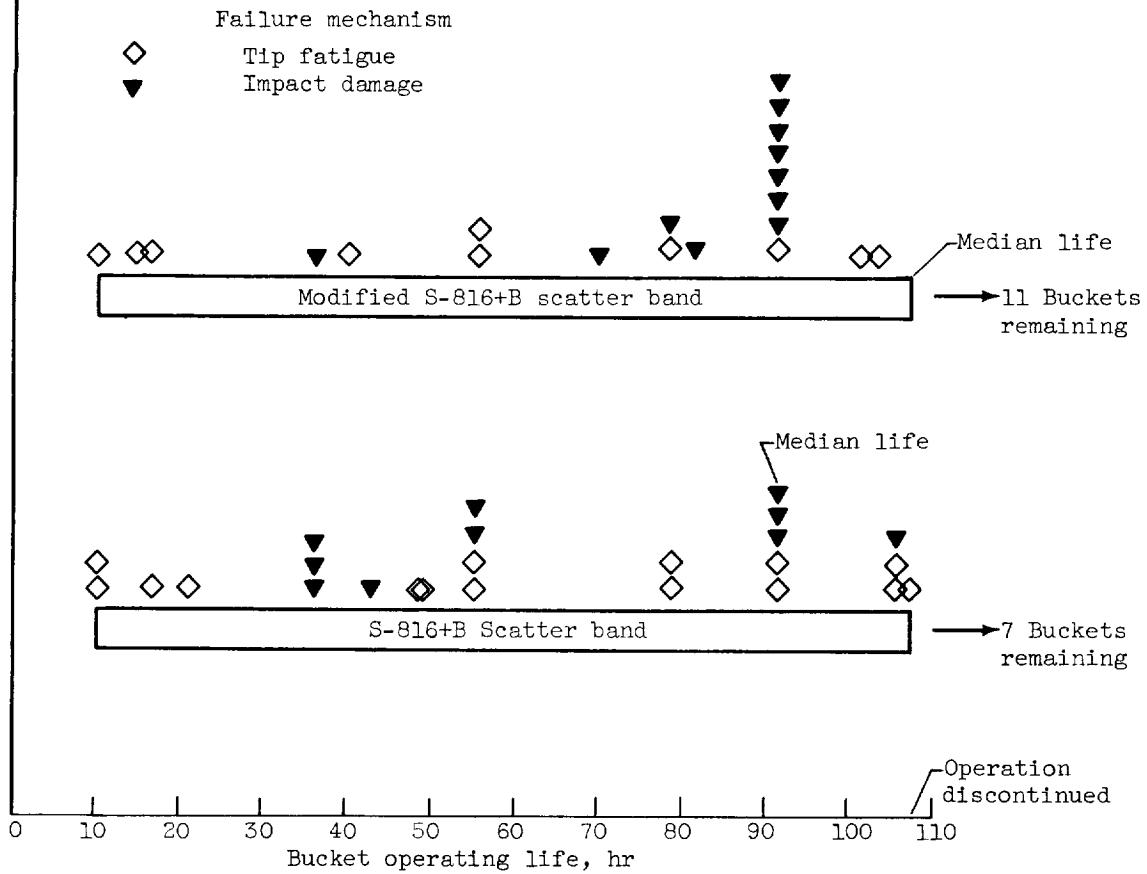


Figure 6. - Performance of S-816+B and modified S-816+B turbine buckets at 1650° F in J33-9 turbojet engine.

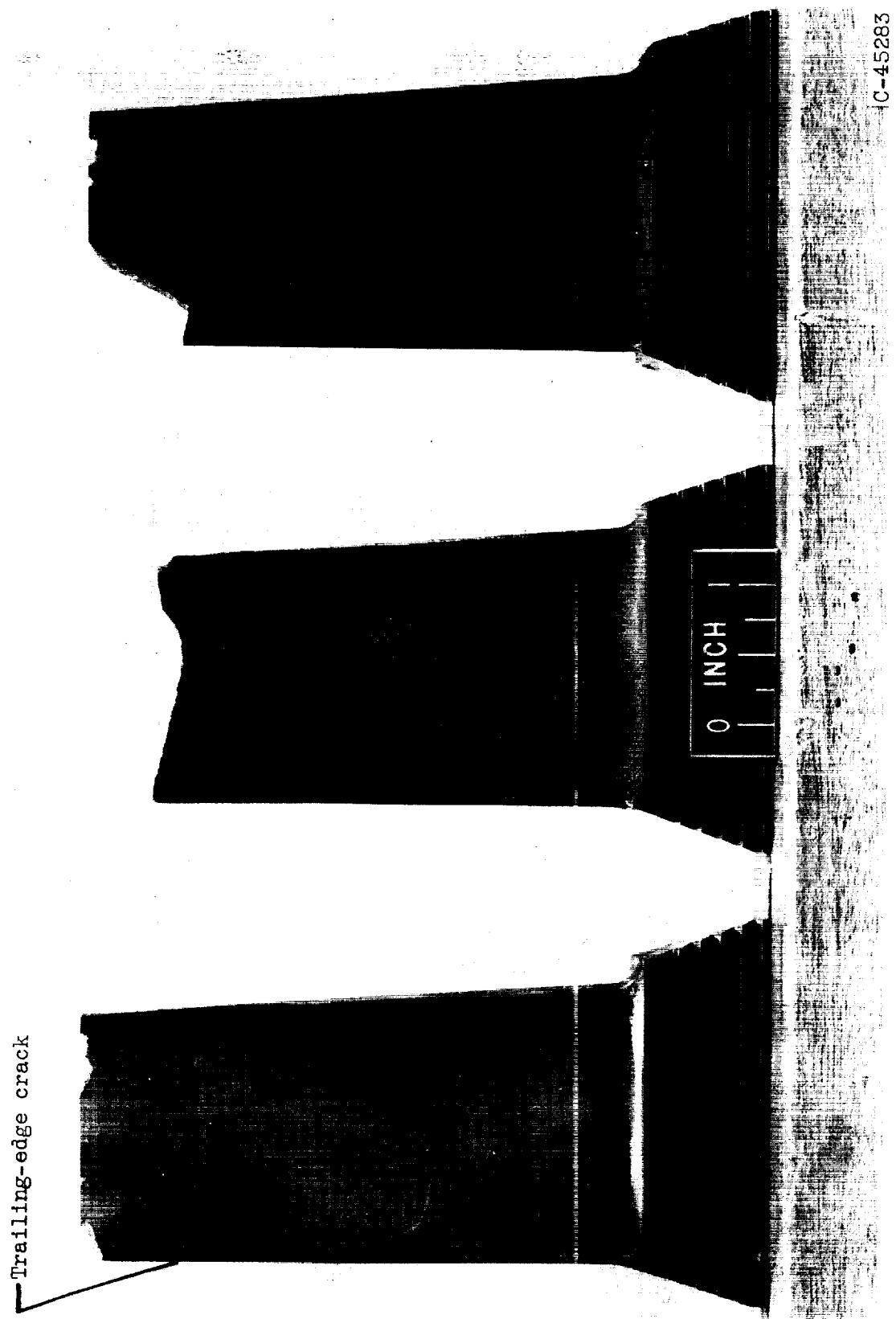
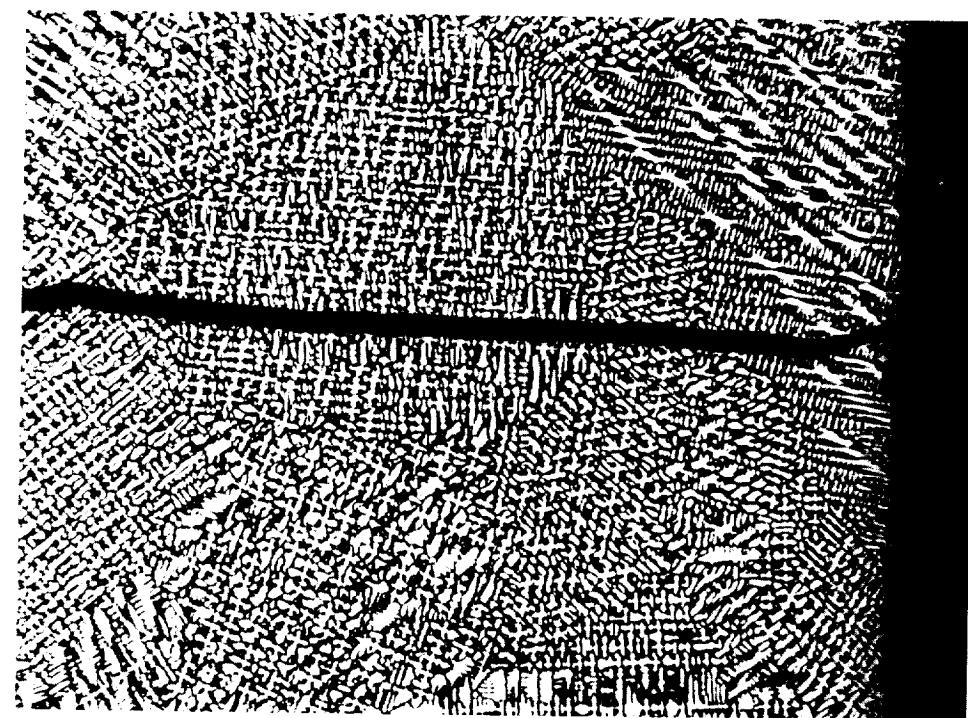


Figure 7. - Bucket failures resulting from trailing-edge fatigue cracks.

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X100



X750

C-49274

Figure 8. - Typical trailing-edge fatigue cracks in engine-operated turbine bucket. Etchant, 20 cc water, 20 cc glycerine, 10 cc nitric acid, and 5 cc hydrogen fluoride.

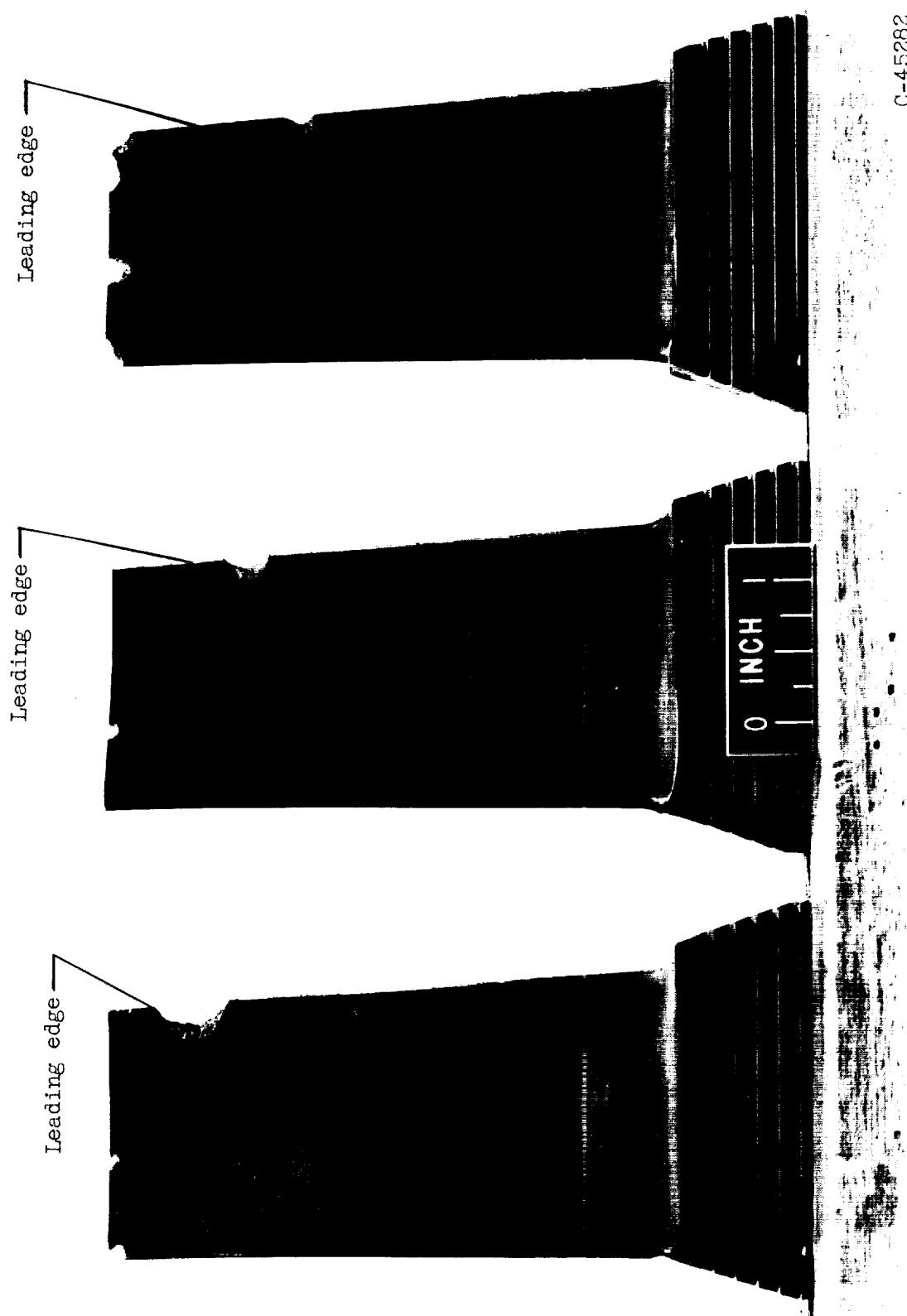


Figure 9. - Typical impact damage to buckets after engine operation.

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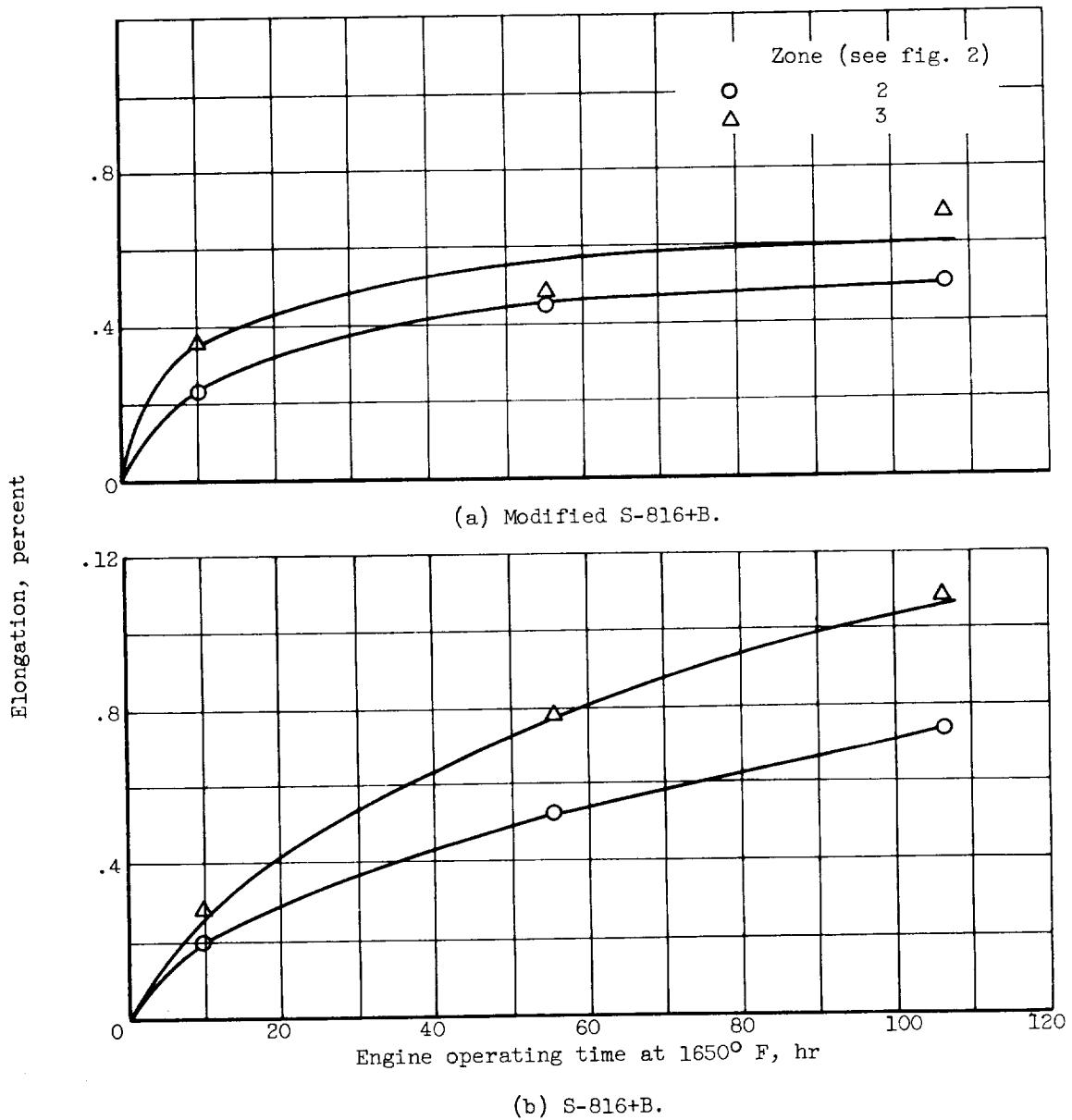
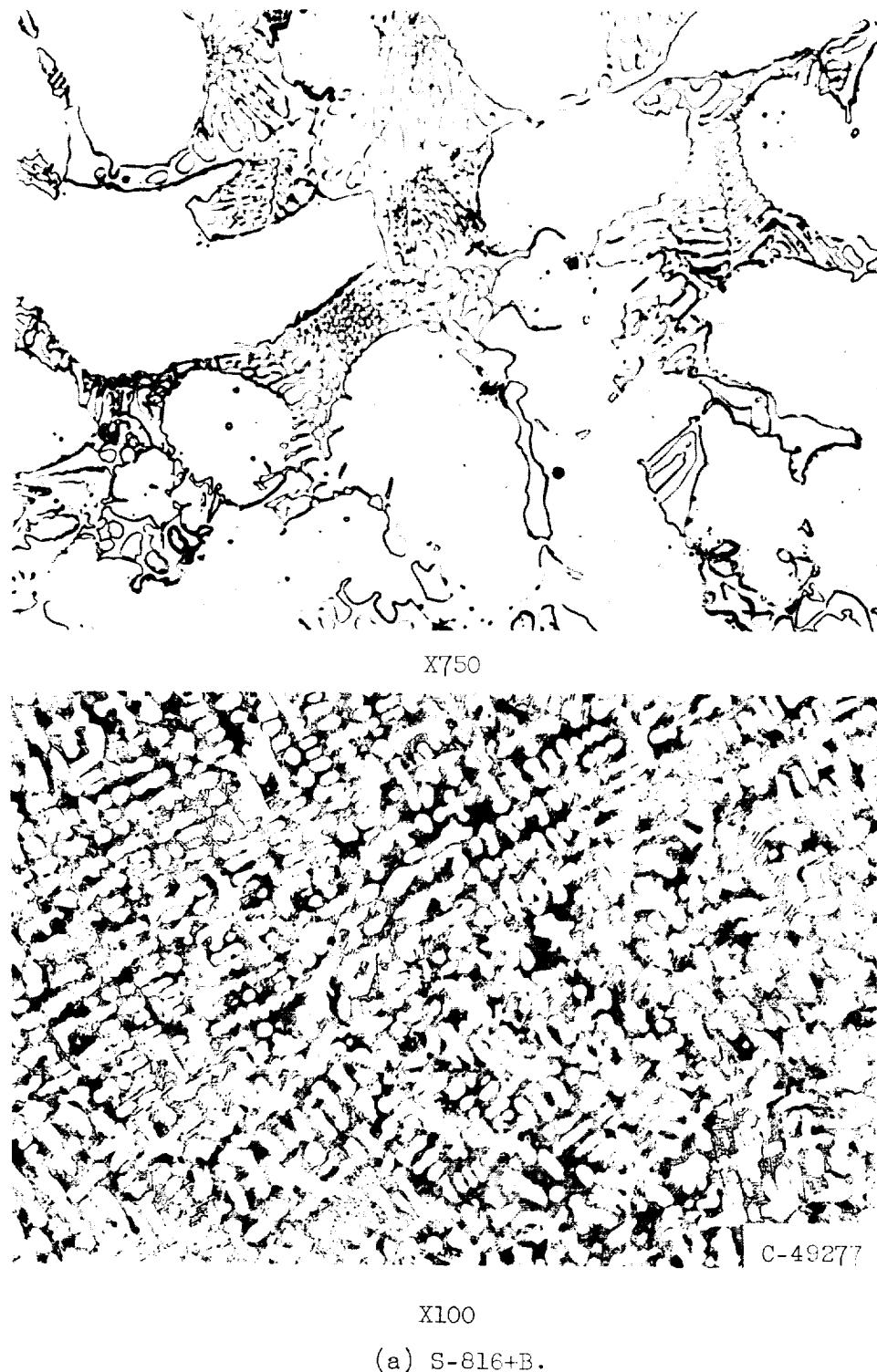
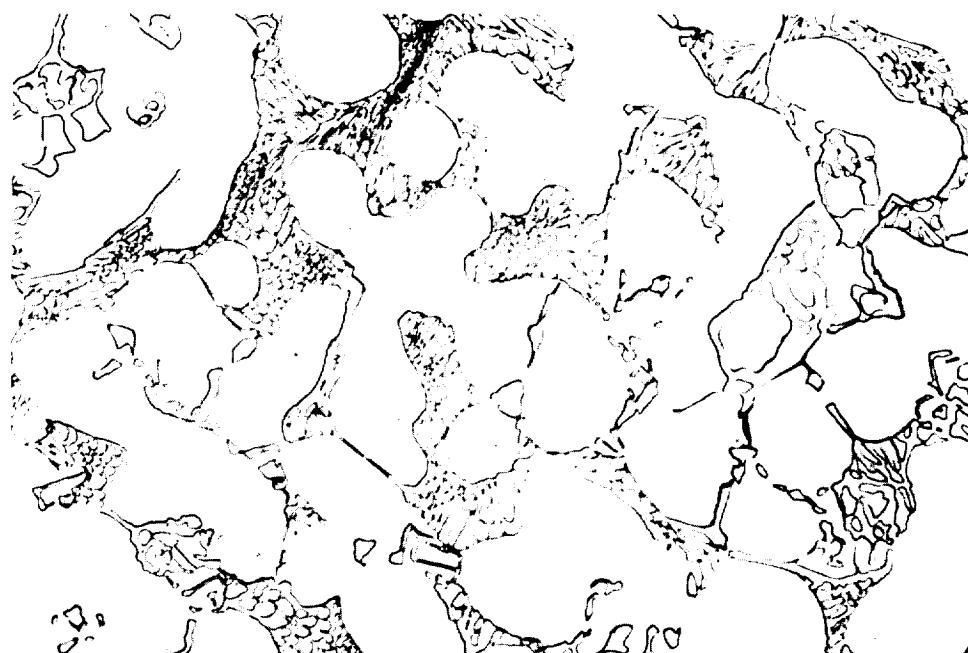


Figure 10. - Elongation rate of midchord section of bucket airfoil.



(a) S-816+B.

Figure 11 . Typical as-cast structures of alloys. Etchant, 20 cc water, 20 cc glycerine, 10 cc nitric acid, and 5 cc hydrogen fluoride.



X750



C-49278

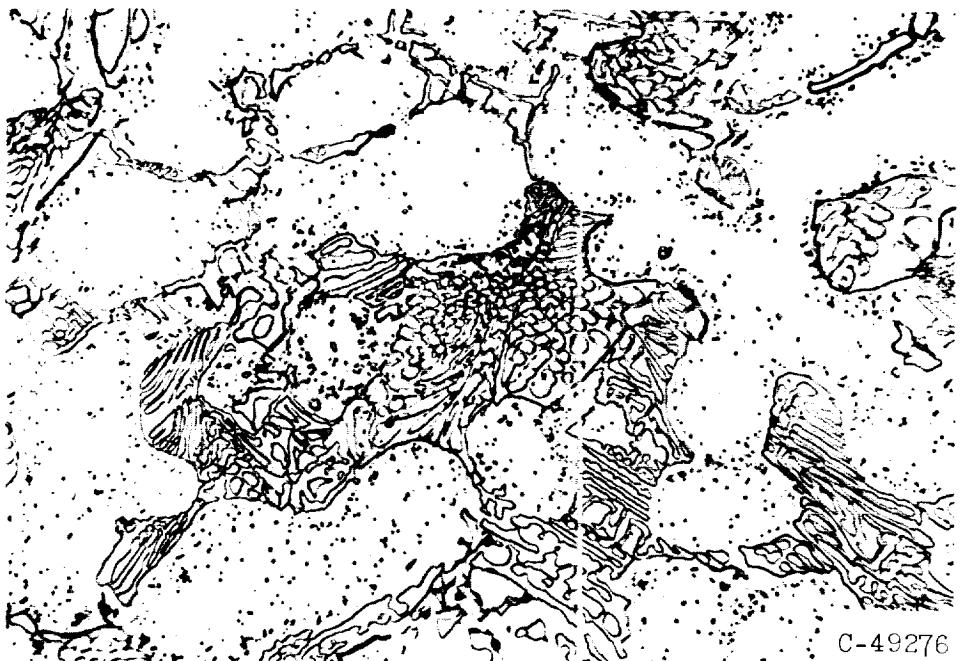
X100

(b) Modified S-816+B.

Figure 11. - Concluded. Typical as-cast structures of alloys. Etchant, 20 cc water, 20 cc glycerine, 10 cc nitric acid, and 5 cc hydrogen fluoride.



(a) S-816+B; engine operated 55.5 hours.

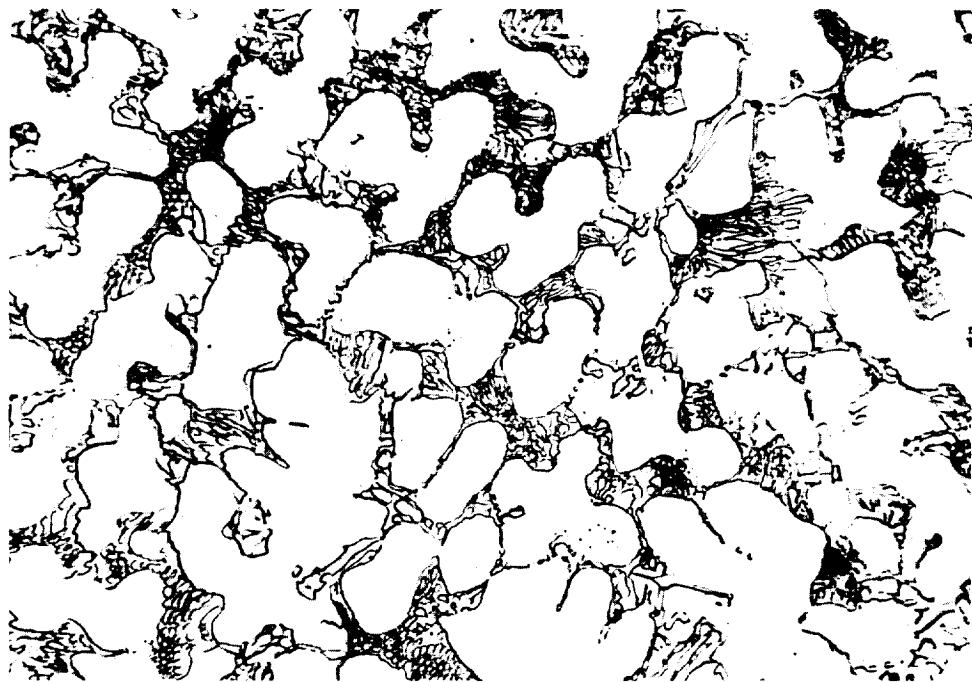


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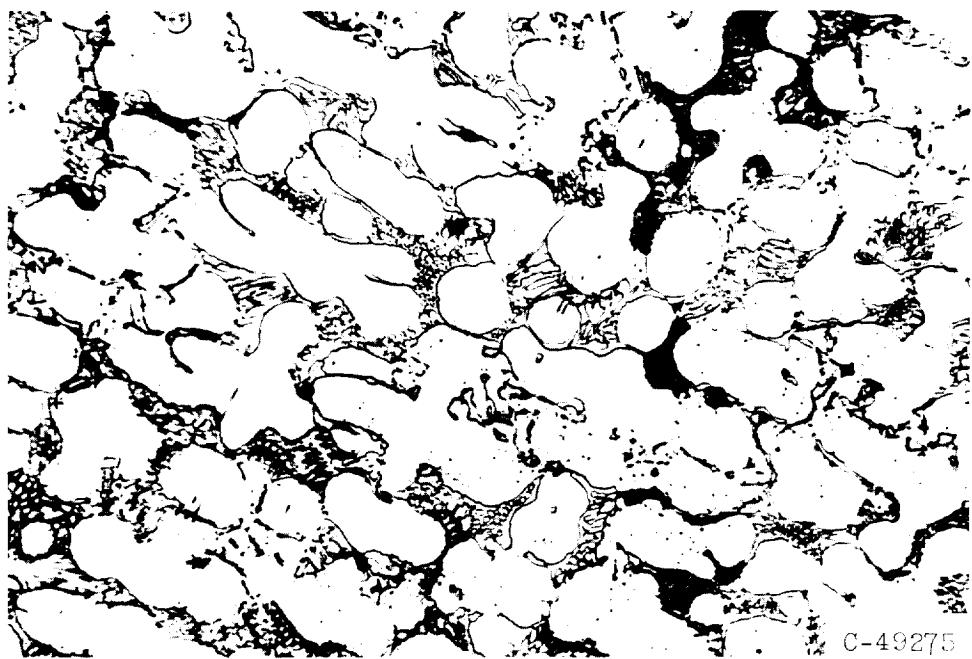
(b) S-816+B; engine operated 107.5 hours.

Figure 12. - Effect of 1650° F engine operation on alloys.
Etchant, 20 cc water, 20 cc glycerine, 10 cc nitric acid,
5 cc hydrogen fluoride. X750.

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(c) Modified S-816+B; engine operated 55.5 hours.



(d) Modified S-816+B; engine operated 103.25 hours.

Figure 12. - Concluded. Effect of 1650° F engine operation on alloys. Etchant, 20 cc water, 20 cc glycerine, 10 cc nitric acid, 5 cc hydrogen fluoride. X750.

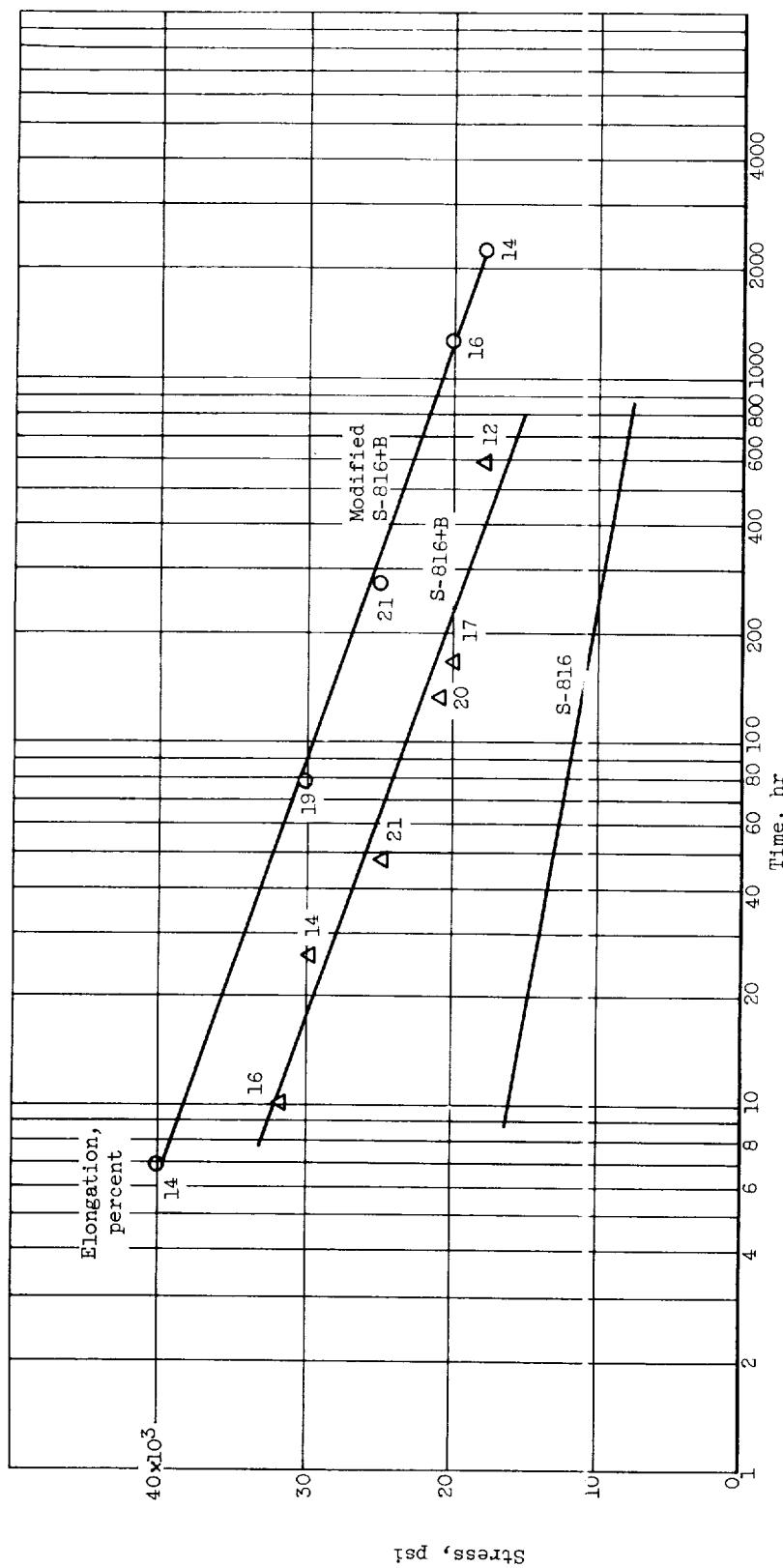


Figure 13. - Stress-rupture lives and elongation at 1650° F for alloys.